Building up stages of a Mediterranean delta: Climatic changes and anthropogenic forcing in the Adra River delta

Episodios de construcción de un delta mediterráneo: Cambio climático y modificaciones antropogénicas en el delta del río Adra

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Abstract: The evolutionary stages of the submarine delta off the Adra River are investigated in this study, under the context of climatic fluctuations entangled with increasing human activities and interventions in the drainage basins and adjacent shores during the Middle to Late Holocene. To achieve that goal, we used an extensive database comprising a set of bathymetric data covering different time slices, a dense grid of high-resolution seismic data and several sediment cores collected in the two submarine lobes of the Adra River delta. Two main evolutionary phases can be identified. The first one extended through most of the construction history and was mediated by major climatic events at the Mediterranean scale; this phase included three major progradational events occurring during the Mid Holocene, the Roman time and the Little Ice Age. The most recent phase is strongly determined by human modifications of the fluvial channels, and resulted in a drastic transformation of the submarine sedimentary environment.

Key words: *Holocene, seismic stratigraphy, submarine delta, human impact, Alboran Sea*

1. INTRODUCTION

Many recent submarine deltaic clinoform wedges have witnessed a considerable development since about 8500 to 6500 years BP, when a substantial sea-level rise deceleration took place and rates of fluvial sediment input increased (Stanley & Warne, 1994). These relatively homogeneous sea-level conditions have been reflected by the formation of sediment wedges typically characterized by a prograding sigmoid geometry (e.g., Liu *et al.*, 2004).

The generation of the prograding geometry results from the interaction of across-shelf and longshore transport processes, such as shifting river mouths of various sizes, and diverse coastal erosion and marine oceanographic processes (Liu *et al.*, 2004, Bárcenas *et al.*, 2015).

The Adra River deltaic system is located in the southeastern coast of the Iberian Peninsula (northern coast of the Alboran Sea, western Mediterranean Basin) (Fig. 1a) and has undergone drastic changes during its evolutionary history, affected both by natural processes and anthropogenic interventions. As thus, natural modifications of sediment supply are likely to be recorded in this system, due to the effectiveness of basin-to-shelf transport processes, enhanced by an abrupt physiography and by the extreme torrential character of the fluvial system (Liquete *et al.*, 2005). In addition, the area has undergone very significant man-driven changes aimed at regulating the fluvial system (Jabaloy-Sánchez *et al.*, 2010). Taking into account all these evidences, we aim to reconstruct its evolutionary pattern during the Holocene Highstand, by tracing back the influence of climatically-driven changes of sediment supply and subsequent interaction with anthropogenic modifications. In order to accomplish that goal, we benefited from an extensive database comprising a dense network of high-resolution seismic profiles that document an unprecedented complex internal architecture of recent deposition, and which enable us to establish a link between coastline changes and the shallow subsurface stratigraphy.

2. METHODOLOGY

Erosion and deposition changes occurring in the area have been estimated at different time scales with the ArcGis software: a) on a secular scale (between 1876 and 2009) and b) on an interannual scale (between 2002 and 2009). The methodology used to obtain the 1876 elevation model (EM) is described in Jabaloy-

Sánchez *et al.* (2010). Bathymetric data used to construct the 2002 and 2009 elevation models were obtained with EM3000D and EM3002D multibeam echosounders, used respectively in the ESPACE02 and MOSAICO0509 surveys.

A total of 254 km of high-resolution profiles were acquired off the Adra River and adjacent areas during the MOSAICO0908 survey with a Uniboom seismic source. These profiles were oriented parallel and perpendicular to the coast, with a lateral spacing of about 1 km.

Sediment cores were collected with a light-weighted vibrocorer during the MOSAICO1108 survey. The cores used in this study were collected off the ancient (MS_V9) and present-day (MS_V4) river mouths at 41.5 and 26.5 m water depths, respectively (Fig. 1b). Three accelerated mass spectrometry (AMS) radiocarbon (^{14}C) datings and grain size analyses were performed in both cores.

3. RESULTS

3.1 Seismic stratigraphy analysis

The subaqueous delta is composed of five seismic units (from older to younger named U5 to U1). These units are fossilizing a Basal Seismic Unit (BSU) (Fig. 1b).

The seismic facies and spatial distribution of most of the seismic units enable the distinction of two lobes: a) the western lobe located off the ancient river course (up to the end of the XIXth century) and b) the eastern lobe located off the present-day river course, which changed in response to river deviations.

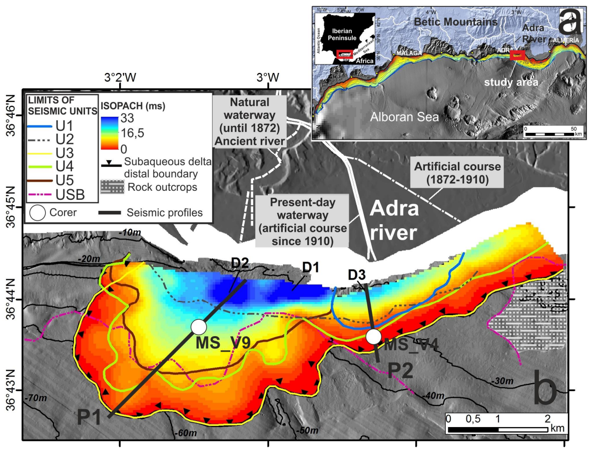

Fig. 1. a) Location of the study area , b) Sediment thickness (in milliseconds) of the entire Adra subaqueous delta with indication of main depocenters (D1 to D3). The Basal Seismic Unit (BSU) distal boundary and the upper boundaries of progradational units (U5-U1) are indicated. The figure 1b show the location of the seismic profiles and sediment cores displayed in Fig. 2

3.1.a Seismic facies

The Basal Seismic Unit (SBU) is bounded at the bottom by a high-amplitude reflector (Sb1) and at the top by an erosive surface (Sb2). This unit is characterized by a wedge geometry, an aggrading configuration, with high-amplitude and discontinuous internal reflectors showing onlap to basal concordance and top erosional truncation (Fig. 2).

The prograding wedge system on top of the USB is composed by seismic units U5 to U1 (Fig. 2) showing distinct seismic facies and distribution patterns in both lobes. These seismic units share several characteristics: a) reflective acoustic response, especially in the proximal areas; b) reflection terminations exhibit basal downlap and toplap to erosional truncation at the top; c) high to moderate thicknesses in shallow water areas decreasing rapidly seaward (Fig. 3); d) wedge to bank external shapes.

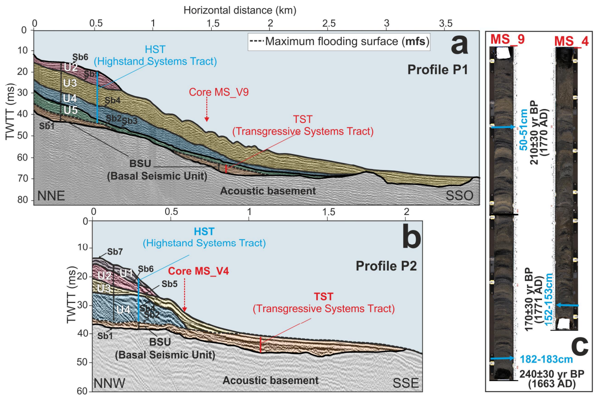

Fig. 2. Stratigraphic architecture of the western lobe (a) and the eastern lobe (b) of the Adra subaqueous deltaic system (across-shelf profiles) with the main seismic units (USB and U5 to U1 units) and major uncorformities (Sb1 to Sb7) and, (c) Cores obtained in the subaqueous deltaic system.TWTT: Double time in milliseconds. See profiles and cores location in figure 1.

3.1.b Distribution of seismic units

The distribution of the seismic units composing the wedge-like submarine delta is characterized by maximum thickness values in the shallower areas, gradually decreasing southward and eastward toward the eastern lobe (Fig. 1b). The highest values (>30 ms) can be observed in two main depocenters (D1 and D2) (Fig. 1b) located to the east of the natural waterway adjacent to the present-day river mouth and off the ancient river mouth, respectively. Another depocenter (D3) is observed off the present-day river mouth with lower thickness (<23 ms).

The BSU occurs parallel to the coastline with a maximum extension off the present-day course (Fig. 3a). The lateral extension is limited to the east by rocky outcrops (Fig. 2b). The sediment thickness of the BSU varies between 0 and 7.7 ms (2.3 ms average value).

U5 is developed only in the western lobe (Fig. 3b) with thickness ranging between 0 and 10.8 ms (2.1 ms average value). The major depocenters occur between the natural and present-day waterways and off the natural river mouth. U4, U3 and U2 are composing both lobes (Fig. 3c-e). U4 and U3 exhibit their maximum extensions in the western lobe (Fig. 3c, d). U4 has a variable thickness (0-13.2 ms; 4.3 ms average value) and the major depocenter is located to the west of the present-day waterway, with a secondary depocenter off the natural course of the river (Fig. 3c). U3 (Fig. 3d) shows thickness values between 0-12.7 ms (3.8 ms average value). The thickness of U2 is higher in the western than in the eastern lobe (average values < 3.8 ms); its maximum thickness value (16.7 ms) occurs between the natural and present-day waterway of the river (Fig. 3e). U1 is present only in the eastern lobe showing the lowest extension and lowest sedimentary thickness (0-3.8 ms) of all the described units (Fig. 3f).

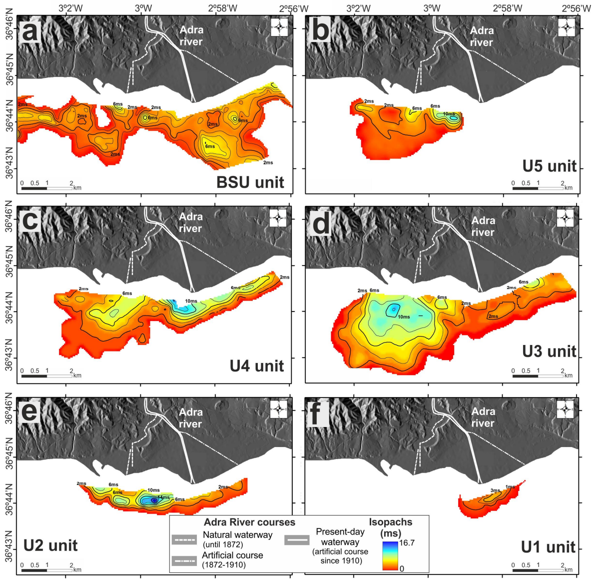

Fig. 3. Isopachs maps (in milliseconds) of the different seismic units composing the Adra subaqueous delta.

3.2 Recent volumetric changes of the Adra subaqueous delta and adjacent areas

A comparison between 1876 and 2009 digital elevation models reveals the accretion of sediments in the eastern lobe and the erosion of the western lobe (Fig. 4a). The sedimentation of around 4.5 x 10^7 m^3 of sediments for 133 years, corresponding to an estimated accretion rate of ~3.3 x 10^5 m^3 yr^{-1}. On the other hand, the total volume of sediment eroded is ~1.5 x 10^7 m^3, which is 1.1 x 10^5 m^3 yr^{-1}. Assuming an average density for the sediments in the subaqueous delta of 1.85 t m^{-3}, the eastern lobe would have accumulated ~6,2 x 10^5 t of sediments during this long period with a minimum sediment yield rate of the Adra River of 0,8 kg $m^{-2}yr^{-1}$ (estimated taking into account the extension of the catchment area)

For a secular period (7 years), the comparison between the bathymetric data shows again the accretion of sediments in the eastern lobe (Fig. 4b). An accretion of 0.1 x 10^7 m^3 of sediments corresponds to an estimated accretion rate of ~1.6 x 10^5 m^3 r^{-1}. In this interval, the erosion is still evident in the western lobe with a total volume of sediment eroded of ~0.9 x 10^7 m^3 and an estimated erosion rate of ~1.3 x 10^5 m^3 yr^{-1}.The minimum sediment yield rate of the river is around 0.3 kg $m^{-2}year^{-1}$ for this period.

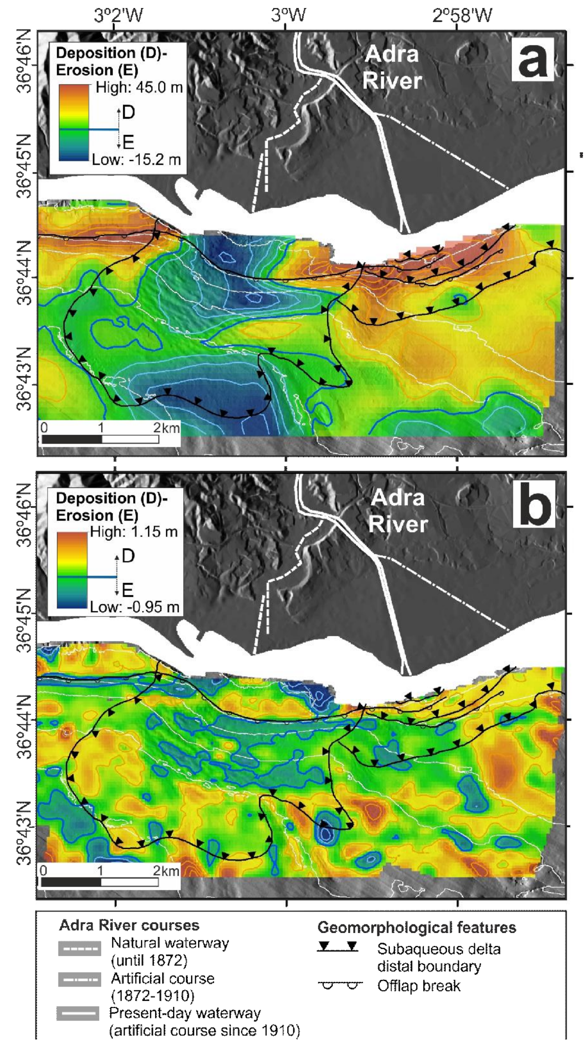

Fig. 4. Recent changes undergone by the submarine portion of the Adra deltaic system. Depositional-erosional areas for the 1876-2009 period (a) and for the 2002-2009 period (b).

3.3 Sediment core data

The ^{14}C date obtained at 182–183 cm depth near the base of core MS_V9 core indicates a conventional radiocarbon age of 240±30 yr BP and a calibrated age of ca. 290 Cal yr BP (1663 AD). The dating from 50-51 cm indicates a conventional age of 210±30 yr BP and a calibrated age of ca. 180 Cal yr BP (1770 AD). In core MS_V4, the level 152–153 cm yielded a radiocarbon age of 170±30 yr BP and a calibrated age of ca. 180 Cal yr BP (1771 AD).

Grain size analyses show that core MS_V9 is characterized by a laminated facies of silt-dominated, fine-grained sediments and sandy silts, with exception of the first ca. 10 cm, where the sand fraction show higher percentages (53-62%). In core

MS_V4 two distinct units are identified. The lower unit is dominated by fine-grained sediments and the upper unit, by more than 90% of sand.

4. DISCUSSION

The formation of depositional units within submarine deltaic wedges during the Holocene sea-level stabilization can be attributed to the dominant imprint of changes occurring in river basins. Wet-dry climatic changes influencing flooding frequency may produce significant modifications of sedimentation rates, leading to lateral depocentre redistribution (e.g., Fanget *et al.*, 2014).

The construction of the different building blocks composing the Adra River submarine delta must be placed in a wider Mediterranean context characterized by different degrees of interaction between climates and anthropogenic activities. The three lower units composing the Holocene deltaic wedge off the Adra River distinctively show lobate distributions, suggesting enhanced terrigenous supply and deltaic progradation. The correlation between the sediment cores and the seismic records seems to indicate that both cores, despite of being collected in different lobes, penetrated the same seismic unit (U3) (Fig. 2). We propose that successive deltaic progradation in the Adra Delta (U5 to U3) occurred coevally with major periods of deltaic progradation around the Mediterranean Basin, occurring during the mid Holocene, the Roman period and the Little Ice Age (Anthony *et al.*, 2014). These major progradations are roughly equivalent to three major period of coastal progradation events documented in the nearby Campo de Dalias coastal plain (Goy *et al.*, 2003). The most recent change to elongated units (U2 and U1) reflects a drastic change in the sedimentation patterns, most possibly triggered by channel deviations.

The larger picture extracted from the Adra River submarine deltaic system documents a progressive change of the depositional system from a classic deltaic environment to shallow-water wedges feeding from partial erosion of the ancient western deltaic wedges and enhanced lateral redistribution. This gradual change is related to increasing human pressure in the drainage basin with a background control of climatic changes leading rainfall events and by extension increased sediment supply and coastal to shallow-water progradation.

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